Towards an Energy Saving MAC for Wireless Body Sensor Networks

Begonya Otal[1], Luis Alonso[2], *IEEE, Member*, and Christos Verikoukis[1], *IEEE, Senior Member*
[1]*Centre Tecnològic de Telecomunicacions de Catalunya (CTTC)*
[2]*Dept. of Signal Theory and Communications, Universitat Politècnica de Catalunya (UPC)*
Emails: begonya.otal@cttc.es, luisg@tsc.upc.edu, cveri@cttc.es

Abstract

Body sensors consume a significant amount of power when data is either transmitted or received. This paper evaluates the energy efficiency per utile bit as a function of the network load and data frame length while introducing power management solutions for a high-performance distributed queuing medium access control (DQ MAC) protocol in wireless body sensor networks. To do so, a new energy analytical model derived from delay theoretical studies is provided. Simulation results are displayed to further validate the protocol energy performance using IEEE 802.15.4 system parameters. The achieved outcome shows that the proposed scheme outperforms IEEE 802.15.4 MAC in all possible scenarios.

1. Introduction and Problem Statement

Whilst wireless sensor networks (WSN) continue to evolve for a broad range of applications from environmental to industrial monitoring, they do not specifically tackle the challenges associated with human body monitoring. Human body monitoring using a WSN may be achieved by attaching sensors to the body's surface as well as implanting them into tissues for a more accurate clinical practice. The realization that proprietary designed WSN are not ideally suited to monitoring the human body and its internal environment has led to the development of wireless body sensor networks (BSN) [1].

One of the major concerns in BSN is that of extremely energy efficiency, since it is the key to extend the life-time of battery-powered body sensors, reduce maintenance costs and avoid invasive procedures to replace battery in the case of implantable devices. Among the several wireless standards available today, the IEEE 802.15.4 PHY/MAC [2] has been considered as the technology of choice for most BSN applications. Although 802.15.4 consumes very low power, the figures may not reach the levels required in BSN.

The 802.15.4 bases channel accesses on the slotted carrier sense multiple access – collision avoidance (CSMA/CA) MAC protocol. In the literature [3]–[5], it has already been proved that the CSMA/CA mechanism has a significant negative impact on the overall energy consumption as the traffic load in a WSN increases. The authors in [3] and [4] show how the 802.15.4 MAC deals with a certain level of data collisions, which steadily increases with the number of sensors in the network, resulting in a progressive reduction of the energy efficiency per utile bit in saturation conditions. In [5], the 802.15.4 MAC standard was further evaluated in dense wireless microsensor networks and an energy-aware radio activation policy was proposed. Additionally, the authors suggested that these physical level improvements should be combined with MAC optimizations that allow for energy-efficient WSN. Thus, the appraisal of other existing MAC protocols in terms of effective energy per utile bit introduces important challenges in either WSN or BSN. That is the reason why we here propose a novel energy-efficiency theoretical analysis and performance evaluation of a different MAC protocol from CSMA/CA, while offering specific improvements for better energy-saving achievements in BSN.

Section II follows with a brief state-of-the-art about the most relevant distributed queuing MAC (DQ MAC) protocols. Section III introduces a significant protocol enhancement to minimize energy consumption by adopting energy-aware radio activation policies. Further, an energy-efficiency theoretical analysis in non-saturation conditions is presented. Simulation results are provided in section IV to evaluate DQ MAC overall energy performance as a function of 802.15.4 MAC system parameters within BSN scenarios. The last section concludes the paper.

978-1-4244-4439-7/09/$25.00 ©2009 IEEE

2. State of the art on Distributed Queuing (DQ) MAC Protocols

The use of the Distributed Queuing Random Access Protocol (DQRAP) for local wireless communications was already proposed in [6] and later in [7]. DQRAP divides the TDMA slot into an "access subslot" that is further divided into access minislots (m), and a "data subslot". The basic idea is to concentrate user accesses in the access minislots, while the "data subslot" is devoted to collision-free data transmission. The DQRAP analytical model approaches the delay and throughput performance of the theoretical optimum queuing systems M/M/1 or G/D/1, depending on the traffic distribution. Hence, the protocol can be modeled as if every station in the system maintains two common logical distributed queues – the Collision Resolution Queue (CRQ) and the Data Transmission Queue (DTQ) –, physically implemented as four integers in each station; two station-dependant integers that represent the occupied position in each queue; two further integers shared among all stations in the system that visualize the total number of stations in each queue, CRQ and DTQ. The CRQ controls station accesses to the collision resolution server (the access minislots), while the DTQ is in charge of the data server (the data subslot), as portrayed in Figure 1. This provides a collision resolution tree algorithm that proves to be stable for every traffic load even over the system transmission capacity. The protocol consists of several strategic rules [6], independently performed by each station by managing these four integers, which answer:

i) 'who' transmits in the data slot and 'when',

ii) 'who' sends an access request sequence in the minislots (m) and 'when'; and

iii) 'how' to actualize their positions in the queues.

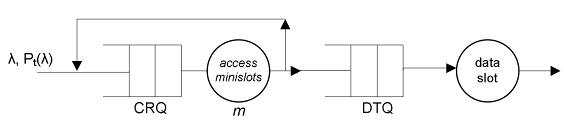

Figure 1. Statistical model of DQ MAC

The promising behavior of DQRAP in [6] and similarly in [7] evokes the idea to further explore DQ MAC protocols in terms of energy consumption under BSN scenarios. This favorable behavior is especially achieved thanks to the inherent protocol performance at eliminating collisions in data transmissions and minimizing the overhead of contention procedures (i.e. carrier sensing and back-off periods). Based on that, we propose a novel DQ MAC energy-efficiency theoretical analysis for non-saturation conditions and evaluate its performance in BSN using 802.15.4 MAC system parameters.

3. Non-Saturation Energy Efficiency Analysis

To be able to asses the average energy consumption of a body sensor in a BSN, we must first characterize the instantaneous power consumption of the transceiver when operating in different states. Apart from the *transmit* and *receive* modes, the transceiver supports two further states: *shutdown,* when the clock is switched off and the chip is completely deactivated waiting for a start-up strobe; and *idle,* when the clock is turned on and the chip can receive commands (for example, to turn on the radio circuitry) [5].

3.1. Energy-Aware Radio Activation Policy

Figure 2 illustrates an adapted frame format to allow different power management scenarios of body sensors using an energy-aware radio activation policy, newly introduced here, for a DQ MAC protocol under BSN.

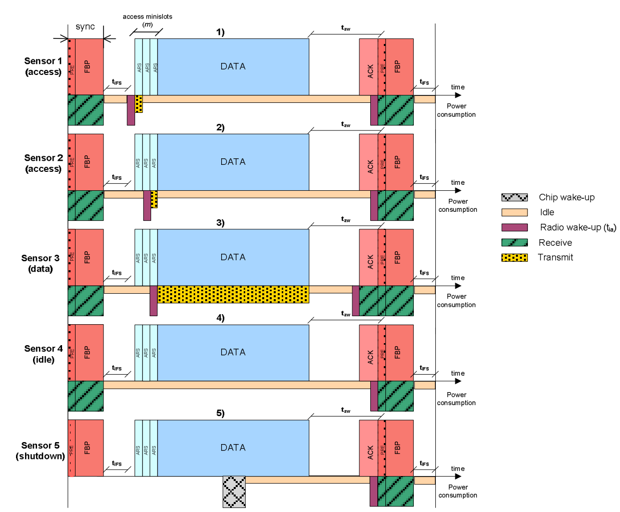

Figure 2. Power management scenarios

Note that each body sensor synchronizes to the BSN thanks to a novel preamble sequence (PRE) of duration t_{PRE} after a period in *idle* mode. Thereafter, it receives the required system information via the feedback packet (FBP) of duration t_{FBP} for updating its distributed queues, CRQ and DTQ [6]. After each

FBP, a short inter-frame space t_{IFS} is left for processing purposes as in IEEE 802.15.4 [2].

Active body sensors involved in the access procedure like in scenarios 1) and 2) start by sending a short access request sequence (ARS), here of duration length t_{ARS}, in one of the randomly selected access *minislots* [6]. Prior to that, these body sensors should have switched its radio from *idle* to *transmit* mode, which take them a transition time t_{ia} for body sensor radio wake-up (i.e. from *idle* to *active* modes [5]). Scenario 3) depicts the transmission of a previously granted packet of duration length t_{DATA} preceded by the transition time t_{ia}. If the packet is received correctly, an acknowledgement (ACK) of duration t_{ACK} is sent back to the transmitting body sensor together with the FBP after a maximum time $t_{aw} - t_{ACK}$, during which the receiver turns its radio to *idle* mode to save energy. In [2], t_{aw} is characterized as the maximum time to wait for an ACK. Scenario 4) shows how an active body sensor waiting in *idle* mode synchronizes through the preamble sequence to receive the FBP. Finally, scenario 5) portrays how a body sensor in *shutdown* state wakes up and waits for some time in *idle* mode to synchronize through the preamble sequence (PRE) and get the FBP to update the state of its CRQ and DTQ queues [6].

3.2. Energy-Efficiency Analysis

Let us first define P_{tx}, P_{rx} and P_{idle} as the power consumption in *transmit*, *receive* and *idle* modes respectively and, similarly $E[t_{tx}]$, $E[t_{rx}]$ and $E[t_{idle}]$ as the average time a body sensor spends in each of the aforementioned modes within the queuing system (CRQ and DTQ). Thus, the average consumed energy per utile bit for every active body sensor in the network can be expressed as $\bar{\varepsilon}_{bit} = \bar{\varepsilon}_{FRAME} / L_{bit}$, where L_{bit} corresponds to the payload data length in bits, and $\bar{\varepsilon}_{FRAME}$ to

$$\bar{\varepsilon}_{FRAME} = P_{tx} \cdot E[t_{tx}] + P_{rx} \cdot E[t_{rx}] + P_{idle} \cdot E[t_{idle}], \quad (1)$$

and where,

$$\begin{aligned} E[t_{tx}] &= E[N_{ARS\_tx}] \cdot (t_{ARS} + t_{ia}) + E[t_{DATA}] + t_{ia}, \\ E[t_{rx}] &= E[N_{waiting}] \cdot (t_{PRE} + t_{FBP} + t_{ia}) + t_{ACK}, \\ E[t_{idle}] &= E[N_{waiting}] \cdot [E[T_{FRAME}] - (t_{PRE} + t_{FBP})]. \end{aligned} \quad (2)$$

The duration of the time frame T_{FRAME} derived from Figure 2 is characterized as,

$$T_{FRAME} = m \cdot t_{ARS} + t_{DATA} + t_{aw} + t_{PRE} + t_{FBP} + t_{IFS}, \quad (3)$$

where m corresponds to the number of *minislots* used in the DQ MAC protocol and t_{ARS}, t_{DATA}, t_{aw}, t_{ACK}, t_{PRE}, t_{FBP}, t_{IFS} and t_{ia} have been previously described following the illustration example of power management scenarios in Figure 2.

Now, we have to identify $E[N_{waiting}]$ and $E[N_{ARS\_tx}]$, which correspond to the total average number of slot time frames *waiting* in the whole queuing system (i.e. CRQ and DTQ), and, the average number of slot time frames *transmitting* ARS in the CRQ system, respectively. Considering the system delay analysis in [8], we define $E[N_{waiting}]$ as,

$$E[N_{waiting}] = E[N_{residual}] + E[N_{CRQ}] + E[N_{DTQ}], \quad (4)$$

where $E[N_{residual}]$ here outlines the average number of residual slot time frames *waiting* in *idle* mode in the system before preamble (PRE) synchronization with the FBP; $E[N_{CRQ}]$ denotes the average number of slot time frames *waiting* in *idle* mode in the CRQ system based on M/M/1 queuing model, which corresponds to the total number of time frames in the CRQ system minus the number of time frames used to transmit the required ARS; and, $E[N_{DTQ}]$ represents the average number of slot time frames *waiting* in the DTQ system based on M/D/1 queuing model [8], which is the total time in the DTQ system minus 1 frame used to transmit the data payload. Hence,

$$\begin{aligned} E[N_{residual}] &= 0.5, \\ E[N_{CRQ}] &= \frac{1}{\ln(1/(1-P_t(\lambda))) - \lambda} - (E[N_{ARS\_tx}] - 1), \\ E[N_{DTQ}] &= \frac{\lambda}{2 \cdot (1-\lambda)}, \end{aligned} \quad (5)$$

where λ is the inter-arrival packet rate (traffic load) and $P_t(\lambda)$ is the probability that a body sensor sends a ARS in a empty access *minislot*, i.e. successfully (see Figure 1 and Figure 2).

Eventually, $E[N_{ARS\_tx}]$ denotes the average number of time frames used to transmit all required ARS during the waiting time in the CRQ system, before a body sensor grants its access into the DTQ system.

We characterize $E[N_{ARS\_tx}]$ as,

$$
\begin{aligned}
E[N_{ARS\_tx}] &= 1\cdot P_t(\lambda) + 2\cdot(1-P_t(\lambda))\cdot P_t(\frac{\lambda}{m}) + \\
&+3\cdot(1-P_t(\lambda))\cdot(1-P_t(\frac{\lambda}{m}))\cdot P_t(\frac{\lambda}{m^2}) + \\
&+4\cdot(1-P_t(\lambda))\cdot(1-P_t(\frac{\lambda}{m}))\cdot(1-P_t(\frac{\lambda}{m^2}))\cdot P_t(\frac{\lambda}{m^3}) + \\
&+\ldots = \sum_{i=1}^{\infty}\left[i\cdot P_t(\frac{\lambda}{m^{i-1}})\cdot\prod_{k=1}^{i-1}\left(1-P_t(\frac{\lambda}{m^{k-1}})\right)\right] = \\
&= \sum_{i=1}^{\infty}\left[i\cdot e^{-\frac{\lambda}{m^i}}\cdot\prod_{k=1}^{i-1}\left(1-e^{-\frac{\lambda}{m^k}}\right)\right].
\end{aligned}
\tag{6}
$$

Based on the same assumption as in [8] that the arriving traffic follows a Poisson distribution in both CRQ and DTQ systems, we have that $P_t(\lambda) = e^{-\frac{\lambda}{m}}$, where *m* corresponds to the number of access *minislots* used in the DQ MAC protocol. This result can be explained intuitively; if the input rate to the CRQ system is λ, then the load to each access *minislot* is λ/m. So the probability of finding an empty access *minislot* is $e^{-\frac{\lambda}{m}}$.

4. Evaluation Study

The performance of the proposed energy-efficient analysis in non-saturation conditions has been validated via MATLAB computer simulations implementing DQ MAC protocol strategic rules as in [6] within a star-base topology and increasing the relative traffic load of the body sensors in the BSN. The reference scenario is defined by the system parameters corresponding to the standardized IEEE 802.15.4 MAC default values in the upper frequency band 2.4 GHz at the fixed data rate 250 Kb/s [2]. Following the illustration in Figure 2, we chose the longest data payload lengths (*L*) of 80, 100 and 120 bytes, to minimize the PHY (6 bytes) and MAC (8 bytes) headers overhead per utile bit. Despite the use of DQ MAC, a packet may be corrupted by bit errors due to noise. Hence, a body sensor waits for an ACK (11 bytes) for a maximum time of $t_{aw} - t_{ACK}$, where t_{aw} is limited to 864 µs, as defined in [2]. The synchronization preamble sequence (PRE) corresponding to 4 bytes will be followed by the FBP of 11 bytes, similar to a beacon frame in [2]. Additionally, we use three access *minislots* like in [6]–[7], and an ARS occupies hereby the same size as a preamble sequence. Power consumption values are formalized as in [5], (i.e. P_{rx} = 35.28 mW, P_{idle} = 712 µW and P_{tx} = 22.09 mW, for a transmit power of -5 dBm).

4.1. Energy Consumption per Utile Bit

Figure 3 portrays the analytical results of the energy consumption per utile bit of DQ MAC versus the 802.15.4 MAC analyzed in [5], as the relative traffic load in the system increases. It can be seen how the use of DQ MAC outperforms 802.15.4 MAC reaching a 37% of energy efficiency improvement when the relative traffic load is as high as 60%.

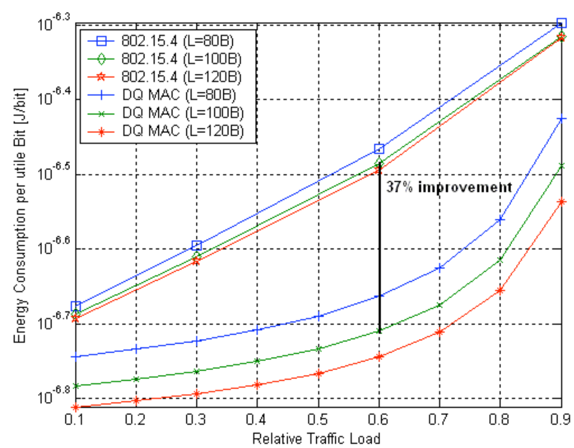

Figure 3. Analytical energy consumption per utile bit – DQ MAC vs. IEEE 802.15.4 MAC

Analytical and simulated results of DQ MAC energy consumption per utile bit are depicted in Figure 4. Here, it can be seen the excellent protocol performance even for the highest traffic load between 80% and 90%, which remains under 350 nJ/bit. Further, simulation results prove the right theoretical analysis of the protocol performance in terms of energy efficiency. Needless to say, the energy consumption per utile bit tends to be minimized by using the maximum packets lengths allowed in the standard. Simulations results corroborate also this fact.

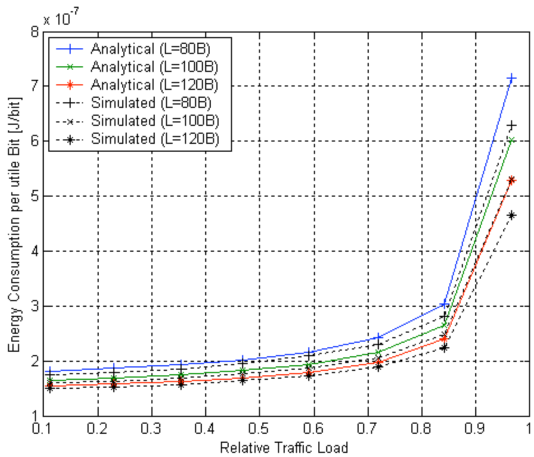

Figure 4. DQ MAC energy consumption per utile bit – Analytical vs. simulated

4.2. Time spent in *idle*, *transmit* and *receive* modes

In order to further evaluate the energy consumption performance of the whole DQ MAC queuing system, we study the time spent in each of the activity modes *idle*, *transmit* and *receive* modes. Figure 5 shows that when the traffic load is higher than 50%, the most critical time is while waiting in *idle* mode (*idle* time).

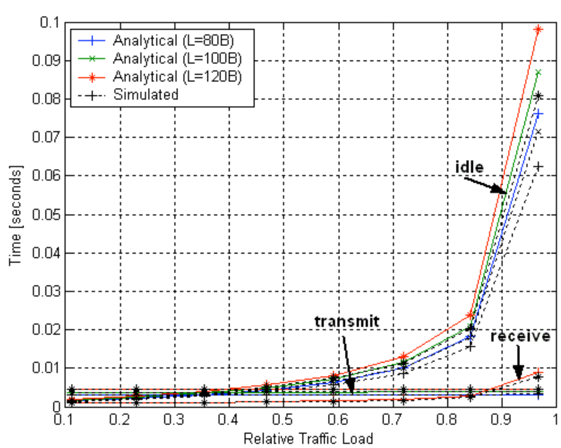

Figure 5. Time spent in *idle*, *transmit* and *receive* modes

Theoretically speaking, minimizing the *idle* time in the system reduces the energy consumption per utile bit. The *idle* mode is the most time-consuming mode in the overall queuing system for high traffic loads due to an increased number of packets in the CRQ and DTQ systems. To minimize the *idle* time in the CRQ system, it might be required to fulfill $E[N_{CRQ}]=0$. From equations (5) and (6), $E[N_{CRQ}]=0$ results in

$$\sum_{i=1}^{\infty}\left[i\cdot e^{-\frac{\lambda}{m^i}}\cdot\prod_{k=1}^{i-1}\left(1-e^{-\frac{\lambda}{m^k}}\right)\right]= \\ =\frac{1}{\ln(1/(1-e^{-\frac{\lambda}{m}}))-\lambda}+1. \qquad (7)$$

Figure 6 portrays the result of (7), which turns to be an inequality for different number of *minislots* (m), as the relative traffic load increases. The bottom dotted line represents $E[N_{ARS\_tx}]$, that is, the average number of time frames used to transmit all required ARS, see (6). Ideally, to minimize *idle* time in the CRQ system, the number of *minislots* (m) should be configurable depending on the traffic load λ. That is to say that for low traffic loads the ideal number is m = 3 as in [6]. However, for traffic loads superior to 50%, it might be better to use a higher number of *minislots* in order to minimize $E[N_{CRQ}]$. That is though implementation dependant.

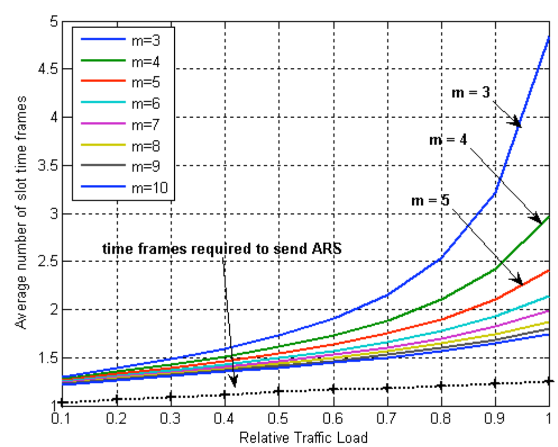

Figure 6. Number of slot time frames in the CRQ system depending on the number of *minislots* (m)

Similarly, to minimize the *idle* time in DTQ (i.e. $E[N_{DTQ}]$), the only possibility is to reduce the packet length, since $E[N_{DTQ}]$ just depends on λ (see Figure 5 and equation (5)). Hence, when the traffic load is high, body sensors in the DTQ system wait longer, the longer the packet length is. Contradictorily, Figure 4 shows that the energy consumption per utile bit is minimized with long packet lengths. Therefore, for high traffic loads, there is a tradeoff among packet length, *idle* time and energy consumption per utile bit, which has to be taken into account in the system design.

5. Conclusions

A new energy-efficiency theoretical analysis for an enhanced distributed queuing medium access control protocol is presented for wireless body sensor networks. For that purpose, energy-aware radio activation policies are first introduced in order to allow power management regulation to minimize the energy consumption per utile bit. The analytical study has been validated by simulation results, which have shown that the proposed mechanism outperforms IEEE 802.15.4 MAC energy-efficiency for any traffic load in all the same scenarios. This favorable energy-efficient behavior is especially achieved thanks to the inherent protocol performance at eliminating collisions in data transmissions while minimizing the control overhead and hence the overall energy consumption per utile bit.

Acknowledgment

This work was supported in part by COOLNESS (218163-FP7-PEOPLE-2007-3-1-IAPP) and TEC2006-10459/TCM.

References

[1]. G-Z. Yang (Ed.), *Body Sensor Networks*, Springer-Verlag London Limited 2006, ISBN-10: 1-84628-272-1.

[2]. *IEEE Std. 802.15.4-2003*, "IEEE Standards for Information Technology Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs)", 1st October 2003.

[3]. T.R. Park, T.H. Kim, J.Y. Choi, S. Choi, and W.H. Kwon, "Throughput and Energy Consumption Analysis of IEEE 802.15.4 slotted CSMA/CA", *Electronic Letters*, 1st September 2005, vol. 41, no.18.

[4]. S. Pollin et al. "Performance Analysis of Slotted IEEE 802.15.4 Medium Access Layer", *Technical Report, DAWN Project*, September 2005.

[5]. B. Bourgard, F. Catthoor, D. C. Daly, A. Chandrakasam and W. Dehaene, "Energy Efficiency of the IEEE 802.15.4 Standard in Dense Wireless Microsensor Networks: Modeling and Improvement Perspectives", *in Proc. Design Automation and Test in Europe Conference and Exhibition*, pp. 196-201, March 2005.

[6]. H.J. Lin and G. Campbell, "Using DQRAP (Distributed Queuing Random Access Protocol) for local wireless communications", *in Proc. Wireless '93*, Calgary, Canada, July 1993, pp. 625-635.

[7]. L. Alonso, R. Ferrús, and R. Agustí, "WLAN Throughput Improvement via Distributed Queuing MAC," *IEEE Communalisation Letters*, vol. 9, no. 4, Apr. 2005, pp. 310–12.

[8]. X. Zhang and G. Campbell, "Performance Analysis of Distributed Queuing Random Access Protocol - DQRAP", 1994, (*Internal Report*).

[9]. http://citeseer.ist.psu.edu/article/zhang94performance.html.